DESIGN CHARACTERISTICS OF A PIEZOELECTRIC/ ER FLUID MOTOR

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Abstract This paper shows the performance characteristics of a new concept in stepper motor technology. Piezo translators [PZT] employed to provide primary motion are connected to a load via a controllable electrorheological fluid [ERF] ratchet. The speed of the motor is governed by either the frequency of the pulse control or the amplitude of expansion of the PZT. Ideal considerations are used to quantify the limiting potential of the drive. Future applications are discussed.

Keywords Electrorheological fluid, piezoelectric translator, electrostatic, mechatronics, robots, motors, actuators.

1. INTRODUCTION

Our research centres upon the principle that electrostatic fields can be used to change the internal properties of matter directly. Thus PZT's increase their size and ERF solidifies when subjected to an electrostatic field. This is what makes such a system directly controllable from a computer in mechatronic applications. Conventional motors are limited in their torque density and they must derive the control of torque-force relationship through a gear system, hence their system efficiency and its precision are reduced, while the size and as well as the weight of the system are increased. Therefore, our department has a great interest in the development of electrostatic motors for robot arms. Potentially, electrostatic devices offer several advantages over conventional devices, such as motors. They can be largely constructed out of plastics. Faster response and greater precision is obtained from pulse switching with real time computer control. It is therefore more suitable for mechatronic applications. See Figure 1 below.

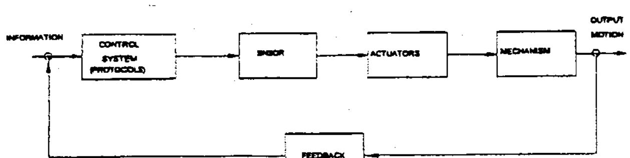

Figure 1 Showing a mechatronic control system

2. STRUCTURE

Figure 2 shows the structure of the motor. The reciprocating motion of paired PZT's is amplified by a lever system and mechanically rectified by twinned concentric ERF ratchets acting in pulsed synchronism with the PZT's to give continuous output motion. Electrorheological fluid is infiltrated between the nesting vibrator and rotor concentric cylinders.

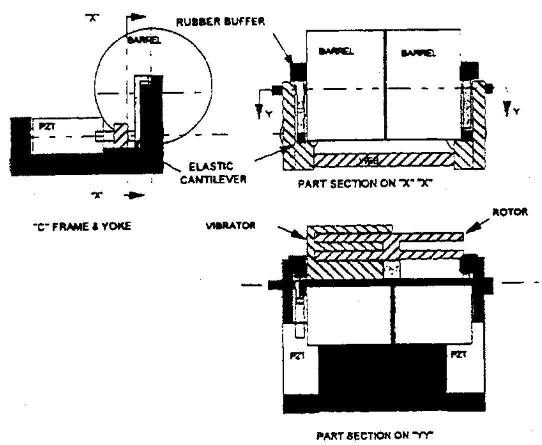

Figure 2 Showing the structure of the motor

2.1 *PZT Drive subsystem*

2.1.1 *Piezotranslator*

A PZT is an electrically controllable positioning element which functions on the basis of the piezoelectric effect. The piezoelectric effect is the ability of certain crystalline materials e.g. barium titanate, to generate an electric charge in the proportion to an externally exerted force. The voltage created can be so great that a spark jumps between two electrodes, an example is piezoelectric lighter. In PZT, the inverse effect is made use of. An electric field is applied parallel to the direction of polarization and effects an expansion of the materials in the same direction. The system utilises this effect to provide required output work. Normal piezo expansion is very small and therefore has to be mechanically amplified to provide useful output motion.

2.1.2 *Piezo Drive*

Piezo translators mounted within "C" frames, have been used to provide precise reciprocating motion when voltage pulses are applied. This reciprocating motion is rectified by ERF ratchets. Since the expansion of the PZT is small, the output motion is magnified about twenty times by means of a compound elastic cantilever system [see figure 3]. Since the PZT's are in stack form, they are weak in tension, torsion and shear loading. Thus a pair of side trust eliminators have been introduced and the system is designed in such a way that the PZT's are always in compression.

2.1.3 *Force / Displacement chain*

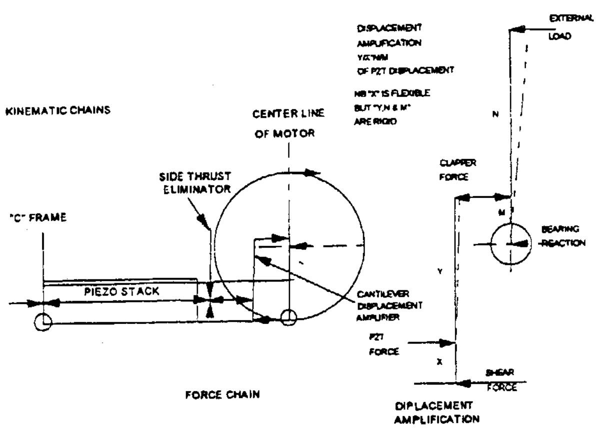

Figure 3 showing the kinematic chain and the displacement amplifier

The PZT output is firstly multiplied by the first part of the compound lever. The lower portion is a bendable elastic hinge cantilevered into the "C" frame while the upper portion is sufficiently rigid not to absorb the displacement. The displacement is amplified by the lever some four to five times. Then the output is further amplified by the second part at the driver barrel by the factor of four to five again. Thus, the output displacement is about 16-25 times of PZT expansion of about 80μm and the available output force is between 1/16-1/25 of the PZT input of about 10,000N.

2.2 *ERF Ratchet*

2.2.1 *Electrorheological fluids*

ER fluids are dispersions of fine polarizable particles in the dielectric liquids that upon application of a high voltage electric field, change rapidly from liquid-like to solid-like behaviour. These fluids were first discovered in 1947 (Winslow). It was determined that the particles in them form a chain-like or fiber-like structure upon the application of the electric field. The strength of the fiber structure is responsible for the increase of the shear strength that results when an electric field is applied.

2.2.2 *Ratchet Design*

The design of the ratcheting system is a compromise between minimising size and maximising torque transmissibility. Shear area has been maximised at a low average radius by summing concentric cylinders. Figure 2 above shows the nesting driver and driven, [or, vibrator and rotor] concentric cylinders with electrical connections. The gap between the cylinders is one half of one millimetre. The applied voltage is around 1.5KV DC.

2.3 *Rubber Buffer design*

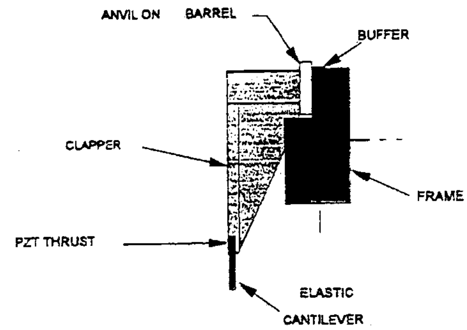

Figure 4 showing the design of the rubber buffer

On the expansion of the PZT, the output work is shared equally by the applied load and the strain energy absorbed by the buffer which is made of rubber pad. The latter is used to provide reversing work energy. As the PZT contracts, the rubber pad gives up its strain energy either as available reverse work if required or as compressive work on the contracting PZT. The PZT is all the time under compressive loading, which acts as a form of preload on the PZT. This is a favourable loading condition for piezo electric stacks.

3. SYSTEM DESIGN

3.1 *Circuit Design*

The programme of motion of the prototype is controlled by an 80286 PC. The step pulse signals are obtained through a parallel interface card and transmitted to power amplifier [Kepco Inc.] which outputs the preset voltage as step voltage for the ERF to perform grip and slip actions. While the sawtooth signals are derived from an 12-bit digital to analogue converter and transmitted to a proprietary piezo power amplifier [Phyzik Instumente GbmH & Co.] which outputs the preset voltage to the PZT and hence fixes the size of the expansion obtained.

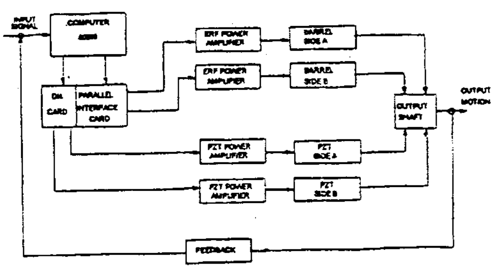

Figure 5 showing the control system of the motor

3.2 *Motion Design*

Primary motion is supplied by paired PZT's, acting alternately, one rising and one falling. Forward motion is obtained by synchronously latching the load carrying barrel with the rising PZT. The motion of the falling PZT is not caught since the ERF of the corresponding barrel is in the off-state which allows the idling barrel to retract to the start position. This yields uniform forward motion. Motion is reversed by a one-off addition to the gripping pulse coincident with the subtraction of the gripping pulse to the alternate barrel, see Figure 6 below.

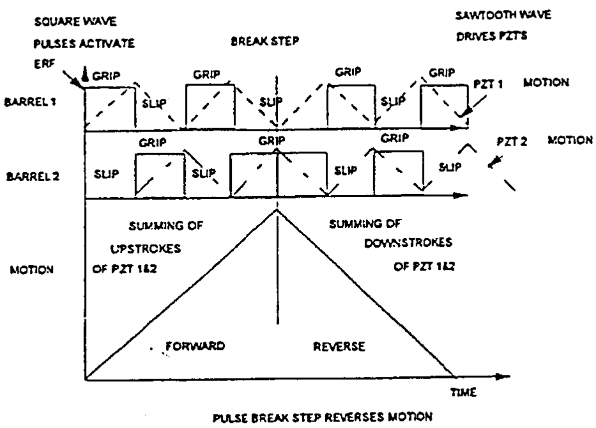

Figure 6 Pulse control of forward and reverse motion

3.3 *Torque Speed Relationship*

The limiting power of the system is 25 W per barrel which is dictated by the electrical power source. The limiting speed is governed by the product of three variables

1. maximum effective frequency [in turn, a function of the ERF properties],
2. the PZT output displacement [80x 10^{-6} m],
3. the value of the displacement amplification [between 16 and 25 times].

Since the limiting power supply is fixed at 25 W per barrel this gives a hyperbolic torque-speed characteristic [since, Power = Torque x Angular velocity] with practical limits at about 3 radians/sec at 8 Nm and 1 radian/sec at 20Nm. See Figure 7 below.

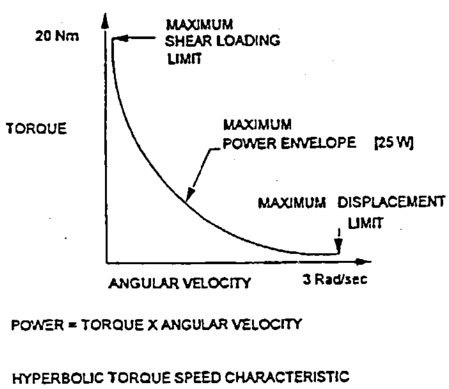

Figure 7 showing the torque-speed characteristics of the motor

3.4 *Other design considerations*

Initially, the design problems posed by the system were, the very small output motion of available PZT's, and the low static yield shear strength of the available ERF [typically around one N/cm^2 i.e. 10kPa]. The first places heavy demands upon the stiffness and the precision of the kinematic chain since any deformation, backlash or running tolerance occurring will absorb part of the minute displacement afforded by the PZT, especially since output forces of PZT's are measured in thousands of Newton's. This has been overcome by the addition of a compound displacement magnifier which takes the form of an elastically hinged cantilever. Without displacement amplification the PZT's would have to be run at high frequencies to give even a modest output speed. High frequencies are problematical in that capacitive reactance varies inversely with frequency leading to excessive current demand. In our experiments values of frequency were kept below 200 Hz. Any inherent weakness in the activated ERF is compensated for by a design which maximises the shear area. Thus the design, based on a nominal yield strength of 10 kPa, resulted in a shear area measured in 100's of cm^2 in order to provide for useful levels of torque output.

4. Discussion and Future Work

The general performance characteristics of the electrostatic stepping motor which are as follows:

1. multi-aspect performance, such as simultaneous position and velocity control of the mechanism. H.K.Tönshoff (1995) showed one possible algorithm in his linear drive system.
2. electronic compensation for random variation in loading conditions.
3. electronically controlled ratchets are substituted for the conventional mechanical gearbox, thus allowing significant reduction in weight and more adaptive and responsive control.
4. wholly electronic function for both forward and reversing motions.

The performance of the motor can improved further in five ways:

1. In future models, the multi-layer aluminum cylinders can also be made of metallic coated plastic cylinders, in which weight will be further reduced.
2. The nominal yield stress of the electrorheological fluid used here is 10 KPa. If stronger fluids can be used, the torque performance will be improved. H.Conrad (1992) showed that the yield strength of the fluid may attain about 50 KPa, and J.B.Yang (1993) showed that the maximum shear strength of his fluid is as high as 58 KPa under the field strength 2MV/m. Hence, the output can be increased dramatically four to five fold.
3. The addition of solid fabric materials to the gap between the cylinders can be another method to increase the yield strength of the fluids. G.J.Monkman (1991) added solid

fabric material to the surfaces of the clutch plates increased the available torque by up to 100%.

4. Reduction of the separation between the cylinders allows the system to run at lower voltages hence it can eliminate the problem of switching high d.c. voltage and has faster response.
5. Changing of the excitation field from d.c. to a.c. may also improve the performance. With the development mentioned above, the motor may be used in simple home appliances. Since a.c. supply is commonly used, the cost in running the system will be cheaper compared with that of in d.c. supply. J.C.Hill (1991) and Y.Hu (1993) had done some experiments on ER fluid with a.c. electric field. They all worked on the phenomenon of ER fluid.

Besides the performance improvement, the motor can be developed towards a reduced size for artificial limbs. Since conventional magnetic motors are heavy, they are not suitable for prosthetic joint motion. Electrostatic motors are simple in structure and can be made of plastics, thus they are lighter and hence more suitable for prosthetic limbs. At the same time the electrostatic motor has a faster response and can be digitally controlled, thus it is also suitable for robotic systems and as well as aerospace automatic systems.

Among the many developments in ER fluid applications, automotive devices are one of the major trends. Hartsock D.L. (1991) has worked out some of the ER fluid requirements for automotive devices. As well as the basic mechanical requirements of the fluid in the system, our concern is energy management. Electronic transmission affords many advantages over conventional mechanical transmissions. The petrol engine still retains many advantages over its electrical counterpart, in particular in terms of power-to-weight ratios. The pulse controlled ER fluid system can further increase this advantage by replacing the gearbox, the crankshaft and the clutch with ERF ratchet.

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